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Enhanced Focusing and Imaging Based on Parity-Time Symmetry and Nonlocality

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Focusing and imaging represent common optical operations. Despite centuries of improvements, however, conventional lenses suffer from inherent limitations, such as limits in resolution, unavoidable presence of aberrations, and challenges in realizing volume-to-volume imaging. These limitations stem, at the fundamental level, from the refraction properties of conventional optical materials. While the advent of engineered metamaterials has opened new avenues to overcome some of these issues, three-dimensional metamaterial lenses have been hindered by their high sensitivity to losses and disorder, inherently rooted in their passive and resonant nature.

In our recent work [1], we have explored a route toward ideal optical systems overcoming these challenges, based on combining the wave physics of non-Hermitian, non-local systems, and the large degree of wave control enabled by engineered metasurfaces. This combination enables a new type of planar lens, composed of a pair of metasurfaces made respectively of absorbing and active elements, satisfying *parity-time symmetry*, which ensures a balanced distribution of optical gain and loss [2]. We demonstrated that, at steady state, the active and passive portions of the system can be designed to operate in concert, independent of the distance between them, to produce unidirectional reflectionless response for all incident plane waves, while the transmitted wave reproduces a specific phase advance determined by backward-propagating modes traveling between the metasurfaces and sustained by the active portion [3]. At steady state, the left (passive) element acts therefore as a coherent perfect absorber [4], completely absorbing the impinging plane waves when illuminated from both sides with waves satisfying a certain phase relation, while the right (active) element operates, at the same time, as a coherently emitting device that provides the required backward-propagating wave. The key ingredient to realize an ideal imaging system consists in tailoring the angular response (nonlocality) of the metasurfaces in order to sustain this operation for all angles of incidence, enabling *all-angle negative refraction and planar focusing*, similar to the response of negative-index metamaterials, but that is intrinsically robust to losses, does not degrade with the lens thickness, and does not require resonant, narrowband inclusions. Such a planar lens realizes aberration-free volumetric imaging, of great interest for optical microscopy, radar imaging, and three-dimensional photolithography. These concepts can also be extended to optical devices for more complex field-transformations and magnified imaging [5-6]. Our findings unveil exciting opportunities enabled by active open systems, for uncharted directions in the centuries-old field of optical imaging.

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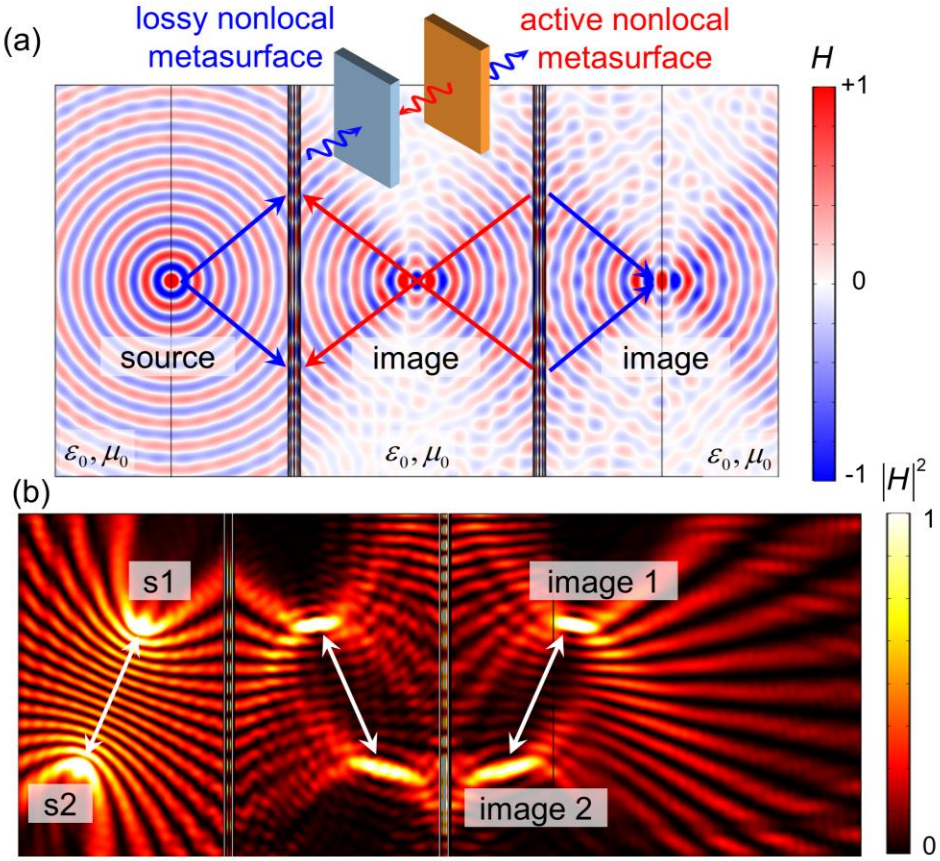

Parity-time symmetric lens composed of a pair of nonlocal metasurfaces with optical loss (left) and gain (right), realizing all-angle negative refraction, planar focusing, and volumetric imaging. (a) Time-snapshot of the magnetic field distribution under point source illumination; (b) Field intensity for two point sources. The transient response for oblique plane wave incidence and for a point source excitation are shown in the accompanying videos.